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Supplementary Materials for

Pathways and challenges for efficient solar-thermal desalination

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Fig. S1. Schematic of energy fluxes in an STD system at steady state.

Table S1. Parameters for the energy balance analysis.

References (135–137)

Derivation of equation 1

For a solar thermal desalination (STD) system, the specific water productivity, SWP ($\text{L m}^{-2} \text{hr}^{-1}$), is defined as the volume of water produced per area of solar irradiation per unit time. Given the solar irradiance, E (kW m^{-2}), solar utilization efficiency for evaporation, η_s , and the specific energy consumption for generation of a unit volume of water, SEC (kWh m^{-3}), SWP can be calculated as

$$SWP = \frac{E\eta_s}{SEC} \quad (\text{S1})$$

There are two steps for water evaporation in an STD process: (i) conversion of solar energy to thermal energy using solar absorbers and (ii) water evaporation using the generated thermal energy. In the first step, the solar-thermal conversion efficiency can be quantified by the solar absorptivity of the solar absorber, α . In the second step, we define the thermal efficiency for water evaporation as η_t . Hence, the solar utilization efficiency for evaporation, η_s can be expressed as

$$\eta_s = \alpha\eta_t \quad (\text{S2})$$

In a thermal desalination process, SEC is obtained from the specific latent heat of water evaporation, L (kWh L^{-3}), and the gain-output-ratio (GOR , dimensionless). By definition, L is the energy required to evaporate one liter of saline water. GOR is an important concept in thermal desalination, defined as the number of kilograms of water produced per kilogram of steam consumed (29). Since the density of water is approximately 1 kg/L, SEC can be calculated as

$$SEC = \frac{L}{GOR} \quad (\text{S3})$$

Combining Equations S1, S2, and S3 yields

$$SWP = \frac{E}{L} \alpha\eta_t GOR \quad (\text{S4})$$

The obtained Equation S4 is Equation 1 in the main text.

Energy Balance Analysis

At steady state, energy balance can be performed in an STD system (Fig. S1)

$$Q_{abs} = Q_{rad} + Q_{conv} + Q_{cond} + Q_{evap} \quad (S5)$$

where, Q_{abs} is the absorbed solar flux (kW m^{-2}), Q_{rad} is the radiative heat loss (kW m^{-2}), Q_{conv} is the convective heat loss (kW m^{-2}), Q_{cond} is the conductive heat loss (kW m^{-2}), and Q_{evap} is the energy utilized for evaporation (kW m^{-2}).

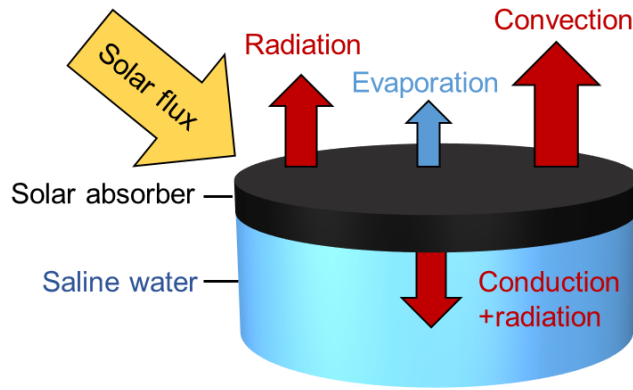


Fig. S1. Schematic of energy fluxes in an STD system at steady state. The yellow arrow represents the incoming solar radiation. The red arrows denote the energy losses due to thermal radiation, convection, and conduction. The blue arrow refers to the energy consumption for evaporation.

The absorbed solar flux, Q_{abs} , can be calculated from solar irradiance, E , and solar absorptivity of the solar absorber, α

$$Q_{abs} = \alpha E \quad (S6)$$

At steady state, the temperature of the feed water should be the same as the temperature of the surrounding environment. The radiative heat loss, Q_{rad} , from thermal radiation to the environment and feed water, can be obtained using the Stefan-Boltzmann equation

$$Q_{rad} = \varepsilon \sigma (T_{abs}^4 - T_{env}^4) \quad (S7)$$

where ε is the emissivity of the solar absorber, σ is the Stefan-Boltzmann constant ($5.67 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}$), and T_{abs} and T_{env} are the absolute temperatures of the solar absorber and the environment, respectively (K).

The convective heat loss, Q_{conv} , and the conductive heat loss, Q_{cond} , can be calculated by

$$Q_{conv} = h_{conv}(T_{abs} - T_{env}) \quad (S8)$$

$$Q_{cond} = h_{cond}(T_{abs} - T_{env}) \quad (S9)$$

where, h_{conv} and h_{cond} are the convective heat transfer coefficient and conductive heat transfer coefficient, respectively ($\text{W m}^{-2} \text{K}^{-1}$).

The evaporation energy flux, Q_{evap} , can be approximated using (12, 135, 136)

$$Q_{evap} = h_{evap}(T_{abs})(T_{abs} - T_{env}) \quad (\text{S10})$$

where $h_{evap}(T_{abs})$ is the evaporative heat transfer coefficient ($\text{W m}^{-2} \text{K}^{-1}$). We note that $h_{evap}(T_{abs})$ is not only determined by T_{abs} , but is also dependent on the solar absorber and system design. In other words, $h_{evap}(T_{abs})$ may vary with different STD systems. For a given STD system, $h_{evap}(T_{abs})$ usually increases with increasing T_{abs} . This behavior can be explained by an increased driving force for water evaporation due to higher vapor pressure difference for high T_{abs} . In our study, we employed an expression for $h_{evap}(T_{abs})$ adopted from literature (38) (see Table S1 below).

Combing Equation S5 with Equations S6-S10 yields

$$\alpha E = \varepsilon \sigma (T_{abs}^4 - T_{env}^4) + h_{conv}(T_{abs} - T_{env}) + h_{cond}(T_{abs} - T_w) + h_{evap}(T_{abs})(T_{abs} - T_{env}) \quad (\text{S11})$$

Based on Equation S11, given E , ε , T_{env} , T_{abs} , and all the heat transfer coefficients, including h_{conv} , h_{cond} , and $h_{evap}(T_{abs})$, T_{abs} can be solved as a function of α . Furthermore, with the obtained T_{abs} , the energy consumptions due to heat losses (i.e., Q_{rad} , Q_{conv} , and Q_{cond}) and evaporation (Q_{evap}) can be specified. The parameters utilized for the energy balance analysis in each scenario (Fig. 4 in the main text) were adopted from previous studies (12, 38, 137), as summarized in Table S1.

Table S1. Parameters for the energy balance analysis (corresponding to scenarios a, b, c, and d in Fig. 4 in the main text).

	a	b	c	d
E (kW m^{-2})		1.0		
T_{env} (K)		293		
T_w (K)	N/A	N/A	293	293
ε	$= \alpha$	0.07	0.07	0.07
h_{conv} ($\text{W m}^{-2} \text{K}^{-1}$)		10		
h_{cond} ($\text{W m}^{-2} \text{K}^{-1}$)	N/A	N/A	50	1
$h_{evap}(T)$ ($\text{W m}^{-2} \text{K}^{-1}$)		$10^{0.0119(T-273)+0.9665}$		

The Relative Insignificance of Interfacial Heating on the Energy Efficiency of Steady-state On-Ground Systems

In a well-insulated on-ground systems with a finite volume of feed water, the energy required to increase the temperature of the bulk water, even by tens of degrees Celsius, is insignificant compared to the latent heat of evaporation ($L = \sim 2400$ kJ/kg at 50 °C). Considering a typical specific heat capacity, c_p , of 3.5 kJ kg⁻¹ °C⁻¹ (exact value ranges from ~ 3 to 4.2 depending on salinity), increasing the bulk temperature of a batch of feed water (Fig. 4A and B in the main text) by a ΔT of 20 to 30 °C requires only 3 to 4% of L for evaporating that batch of feed water. In addition, this small amount of additional energy is only consumed in starting up the system, as heat is no longer transferred to the feed water in an insulated reservoir once steady state is reached. The energy required for increasing the bulk feed solution temperature can become significant compared to the latent heat of evaporation only if (i) the water recovery is very low (i.e., only a very small fraction of the feed water is recovered and becomes product water) and/or (ii) the feed reservoir is poorly insulated so that heat is continuously lost to the ambient environment. Neither case should apply to a well-designed, non-floating STD system.